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APPLICATION OF DISCRETE EVENT SIMULATION TECHNIQUES FOR PRIORITIZATION OF U.S. AIR FORCE MILITARY FAMILY HOUSING PROJECTS

A Thesis

by

HARRY J. KRUKENBERG

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

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ABSTRACT

Application of Discrete Event Simulation Techniques for Prioritization of U.S. Air Force Military Family Housing Projects. (December 1996)

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Chair of Advisory Committee: Dr. Robert E. Shannon

This study, through the use of discrete event simulation and modeling, explores various prioritization disciplines for U.S. Air Force Military Family Housing maintenance, repair, and renovation projects. Actual data from the Military Family Housing Real Property Maintenance Model database are used to build the simulation model. The model is run using various queueing disciplines which represent the various project prioritization disciplines available to the installation Civil Engineer. The current, or standard, prioritization discipline is repesented by a simple first in-first out queue. Alternative disciplines queue the projects according to estimated project cost and estimated project completion time. Comparisons between the standard model and the various alternatives are conducted using paired-*t* tests on two primary and one secondary performance characteristic. The results of this study show that when projects are ranked according to low value first with respect to estimated project cost, significant improvements are realized.

DEDICATION

I wish to dedicate this work to my lovely wife Linda and my daughter Allison, without whose constant love, support, and understanding this work would not have been possible.

ACKNOWLEDGMENTS

I would like to thank the members of my committee for their support and guidance throughout the course of this project. To Dr. Robert Shannon goes special thanks for his expertise and wisdom in the area of simulation and also for giving me the freedom to establish my own goals and objectives for this project. I would also like to extend special thanks to Dr. Don Smith for stressing to me the primary purposes of a simulation study very early in this project. Finally, I would like to express my sincere gratitude to Mr. Robert Gaias, Mr. Steve Essig, and all of the other people at Delta Research Corporation who helped me to obtain the critical input data for this study. Without their hospitality, generosity, and unselfishness; this study would not have been possible.

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CHAPTER I

INTRODUCTION

As the inventory of government owned and operated military family housing (MFH) on U.S. Air Force bases grows increasingly older, there is greater need for both regular operational and maintenance work as well as major reconstruction projects on existing housing units. Furthermore, as this list of projects grows, the installation Civil Engineer is faced with the problem of prioritizing projects such that the maximum number can be completed in a given fiscal year and available resources are utilized most efficiently. This prioritization problem is not merely from an optimization viewpoint of the Civil Engineer; but is also critical for justifying the required financial resources to complete these projects.

This study will focus on the prioritization of MFH projects by applying discrete event simulation and modeling techniques to a typical base's MFH project list. By doing this, the Civil Engineer will not only be able to see how to effectively utilize available funds, but he will also be equipped with a scientifically formulated prioritization scheme. This scheme can in turn be used to justify work priorities to the base leadership as well as justifying funding requirements to higher headquarters.

Currently, the Civil Engineer is limited to executing projects solely according to the amount of project funding that is received. Historically, this funding has been

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appropriated on a "fair share" basis by distributing funds based on the number of housing units on the installation rather than allocating funds based on renovation project requirements. The problem is that for some installations the funding is seldom sufficient for the amount and types of projects that exist at any given time. At the same time, other bases may receive more funding than they need. The Air Force is working on this problem by establishing the Real Property Maintenance (RPM) Model. RPM consists of a central database that will provide an estimate of the types and amounts of projects that are the top priority for each base in a given year (McClellan, 1996). By doing this, the appropriate amount of funding can be sought based on the individual needs and priorities of each installation.

At the base level, however, the need still exists to prioritize the given year's projects so that the Civil Engineer can ensure the most efficient use of resources. Currently, projects are executed once they are programmed and funding is received. This resembles a first in-first out (FIFO) queueing discipline. This study will examine several alternative queueing disciplines and compare them to the current FIFO discipline.

OBJECTIVES

The primary objective of this study is to show how existing RPM model data and simulation modeling can be utilized by the installation Civil Engineer to prioritize Military Family Housing projects. The RPM model data is used as the basis for developing and manipulating a discrete event simulation model. By using previously developed and proven methods (i.e. simulation), this study will show how simulation

can be employed to accomplish two objectives for the installation Civil Engineer. First, a fact-based prioritization of projects can be accomplished based on real RPM model data and simulation results. This prioritization will lead to more effective utilization of available resources. Second, the simulation results can then be used as a resource advocacy model to defend project selection to the base leadership as well as justifying funding requests to higher headquarters.

More generally, it is hoped that this study will inspire and further more widespread use of simulation and modeling techniques in military engineering applications. This study demonstrates how simulation and modeling techniques can have a significant impact on the management and analysis of installation-level Air Force Civil Engineering processes.

SIMAN

The simulation language used to model and analyze the Military Family Housing project process is SIMAN. The developers of SIMAN, Pegden, Shannon, and Sadowski (1995), describe the language as a general purpose language capable of modeling discrete, continuous, and/or combined systems. SIMAN is based upon a logical modeling framework that segments the simulation problem into two components, the model and the experiment. This modeling framework is based on the theoretical concepts of systems as developed by Zeigler (1976). The model component provides a description of the physical elements of the system and their interrelationships. The experiment component is used to set the experimental conditions under which the model will run. These conditions include such things as initial conditions, length of the run,

resource availability, and the type of statistics to be gathered. The analyst's specifications for things such as schedules of resource availability, routing of entities, and queueing disciplines are also included in the experiment component. By separating the model from the experiment in this way, the analyst can easily change the experimental conditions without altering the basic model.

Once the analyst defines the model and experiment components, SIMAN links and executes them to generate the simulated response of the system. As the simulation runs, SIMAN automatically stores the responses specified in the experiment. The simulation response can then be analyzed through the use of the SIMAN summary report or by using the SIMAN Output Analyzer. This feature allows the analyst to conduct comparative analyses and generate plots, histograms, correlograms, and confidence intervals from the saved data.

CHAPTER II

LITERATURE REVIEW

Application of simulation and modeling techniques for military construction project prioritization has been extremely limited. The main reason for this is that the problems encountered in this type of prioritization situation are often unique to government appropriation and construction systems. Projects are not evaluated and selected or rejected based on economic factors as they would be in the private sector, therefore, these same economic factors cannot be used to prioritize the projects. As a result, the project selection and prioritization process is often driven solely by political, budgetary, and environmental pressures.

The main tool used in this study to develop a suitable prioritization scheme is discrete event simulation and modeling. There has been a great deal of work done in this area. Works by Pegden, Shannon, and Sadowski (1995) and Law and Kelton (1991) are used extensively in this study for development of the basic simulation model. Pegden et al. (1995) provide a solid basis of general simulation methodology through the illustration of the use of a specific simulation language - SIMAN. Law and Kelton (1991), on the other hand, focus on basic simulation methodology, independent of a specific simulation language. In addition, works by Sadowski (1989) and Dietz (1992) provide helpful guidelines for the development of successful and accurate simulation projects.

Traditionally, simulation and modeling tools were developed to simulate and analyze manufacturing and/or production oriented processes. However, as computer

hardware and software has become more sophisticated, potential applications for detailed simulation studies have rapidly expanded. Thompson (1994) explains how simulation is no longer simply a planning and design tool. He states that these are only the first two phases of a four phase process by which most projects can be characterized. His main point is that simulation can have profound effects in the implementation and operational phases of a project as well.

Several authors have extensively developed simulation software and techniques for use as construction management tools. These works are closely related to the types of tasks which will be examined in this study. Woolery and Crandall (1983) present their "Stochastic Network Model for Planning Scheduling" which consists of a model of independent and dependent random variables used to provide construction scheduling and planning control for complex projects. The authors model the various tasks of the construction project as a network of activities. The network model is based on Monte-Carlo simulation in which data for each network activity consists of a time distribution for the activity under ideal conditions and a series of time distributions for various problems which may lengthen the activity completion time.

Halpin (1977) developed the CYCLONE (CYCLic Operations NEtwork system) and later MicroCYCLONE simulation languages for modeling repetitive activities common to a construction job site. The author stresses that activities involving the cyclic movement of productive units (e.g., trucks, cranes, and work crews) are the essence of most construction projects from which most process characteristics

can be derived. Thus, these cyclic activities are of primary concern to management and should be the focus of the simulation model.

AbouRizk and Halpin (1990) and (1992) have developed more detailed guides which build upon Halpin's original work. In the first, a basic but detailed guide for developing a construction oriented simulation model is presented. The paper recognizes that most simulation models in construction can be treated as stochastic models. The proper analysis of such models requires: (1) Application of input modeling techniques; (2) appropriate analysis of output parameters based on multiple runs; and (3) validation and verification of the results.

AbouRizk and Halpin (1992) focus on the statistical characteristics of construction data to be used in simulation models. A significant result of this research indicates that flexible distributions (e.g., the beta distribution and Pearson system) are best suited to ensure proper modeling for the diversified characteristics of construction duration data. However, these distributions can only be applied in a data-rich environment in which actual process observations or historical observations can be obtained. The authors stress that when observations are not available, the analyst must rely on the subjective judgment of a person knowledgeable about the process. In this case, uniform or triangular distributions should be applied.

Most recently, highly specialized simulation systems have been developed for construction planning applications. Morad and Beliveau's (1991) "Knowledge-Based Planning System" integrates artificial intelligence (AI) technology with computer-aided design (CAD) to generate and simulate construction plans. The system was designed to

replace the network-based techniques such as program evaluation and review technique (PERT) and the critical path method (CPM) with a more dynamic planning tool. Similarly, Sawhney and AbouRizk's (1995) "HSM (Hierarchical Simulation Modeling)-Simulation-Based Planning Method" enhances and combines the concepts of work breakdown structure (WBS) and process modeling to arrive at an advanced framework for planning construction projects.

CHAPTER III

SIMULATION

BACKGROUND

Currently, the Real Property Maintenance (RPM) Model is in continued development by the Housing Directorate of the Air Force Civil Engineer at U.S. Air Force Headquarters (McClellan, 1996). The RPM model consists of a database which contains information regarding the condition of military family housing at every U.S. Air Force installation worldwide. Survey teams were tasked to visit the bases and survey a statistical random sample of housing units to get a detailed assessment of overall housing condition. The units surveyed were evaluated in ten distinct areas or subsystems including roof, major and minor structural, mechanical, electrical, general interior, kitchen, baths, house sitework, and special assessments. Each of these subsystems had up to fifteen unique characteristics which were evaluated separately based on seven weighted attributes including appearance, condition, functionality, expansion capacity, life expectancy, energy compliance, and safety. By rating the units in this way, an overall weighted average score for each unit's subsystems could be obtained while at the same time detailed subsystem data was maintained.

At the present time, the RPM model is being used at the Major Command (MAJCOM) and Air Staff levels to identify housing requirements. It is also being used to justify funding for housing maintenance and repair as well as new construction. The model was used extensively to successfully support and justify budget requests for fiscal

years 1997 and 1998. Future RPM models will incorporate life-cycle data which will enable accurate estimation of future requirements without repeating the costly surveying process on an annual basis.

Despite the monumental advantages that the RPM model has provided higher headquarters in terms of funding justification and prioritization, the RPM model has not had widespread use at the installation level. The main advantage of the RPM model to the installation is that Civil Engineers are now provided with levels of funding which more accurately address housing needs. The need still exists, however, to provide a way for the installation Civil Engineer to prioritize the requirements identified by the RPM surveys which will more efficiently utilize available funding. The application of discrete event simulation and modeling techniques can hopefully provide a means to efficiently and effectively prioritize projects. Currently, there is no widespread use of simulation and modeling techniques at the installation level.

The installation chosen for this study is Barksdale Air Force Base (AFB), Louisiana. This base was chosen for several reasons. First, the inventory of military family housing is large and diverse. The base has housing built from various MFH appropriations over the past 65 years. But perhaps most importantly, the RPM model data for this installation is the most current and comprehensive compared to all other installations to have undergone the RPM surveys in the past year.

ASSUMPTIONS

The following assumptions were made when formulating the simulation model and conducting the analysis:

1) The model with the FIFO queueing discipline is considered to be the standard model to which all other models will be compared. This model most accurately represents the current real system. Hypothesis tests are conducted for comparison of means and variances between the standard model and each of the alternative models.

2) Primary performance measures used to compare the models include the total number of houses completed over the planning horizon (simulation run length) and the average number of houses waiting for service. Time in the system is also considered as a secondary performance measure.

3) The MFH turnover rate at Barksdale AFB remains constant at approximately twenty-four percent per year. This is a uniform turnover rate for all house types and sizes.

4) Due to the absence of historical data, triangular distributions are used extensively to model interarrival time, project cost, and estimated completion time distributions. Several authors including Pegden et al. (1995) and Law & Kelton (1991) recommend the use of the triangular distribution when attempting to represent a process for which data are not readily available but for which bounds and most likely values can be established based on knowledge of the process. Sufficient data from expert sources was available to verify that these distributions are unimodal and to establish maximum, minimum, and most likely estimates for the parameters of the triangular distribution.

5) MFH renovation and construction costs will remain constant over the next three years. Any inflationary rises in construction costs will be compensated for by adjustments in the budget.

6) With the possible exception of inflationary increases, MFH renovation, maintenance and repair budgets will remain constant over the next three years.

7) Overall housing conditions will not change significantly over the next three years.

8) Contractor availability is not a significant constraint on the system. Obviously, when a project is allocated funds and is delayed for renovation, work crews must be assigned to complete the work. It is assumed that there will be no shortages of work crews which will cause a house to wait for service.

9) If a house requires work on more than one subsystem, all subsystems begin work at the same time.

10) Funding for housing maintenance, repair, and renovation is allocated in a single lump sum at the beginning of the fiscal year.

PROCEDURE

The procedure used in this study involves the application of simulation and modeling techniques to the MFH project list at Barksdale AFB, Louisiana. This is accomplished through five major steps including: (1) Collection and analysis of input data, (2) Formulation of the simulation model, (3) Performance of pilot runs, verification, and validation of the model, (4) Performance of production runs, and (5) Analysis of simulation output.

Collection and Analysis of Input Data

Before any of the data could be analyzed, it was necessary to classify each house as one of 10 house types based on grade (i.e. Junior or Senior Officer, Junior or Senior Non-Commissioned Officer (NCO), etc.). Next, each of the subsystems of interest had to be identified. These included roof, structural, mechanical, electrical, general interior (excluding kitchens and baths), kitchen, and bath subsystems. Table 1 provides a description of each subsystem and illustrates the input data requirements for this model.

The input data has three major components derived from several sources. Each of the components are grouped according to subsystem and house type. The first component is the actual MFH condition data for Barksdale AFB as identified by the RPM surveys. This data was collected by Delta Research Corporation of Niceville, Florida and was obtained from them in database format. The data was then analyzed in order to form discrete proportions of the various subsystem requirements for each house type. For example, for the roof subsystem data, overall proportions of roof condition codes for each house type were determined from the various roof characteristics and attributes ratings. Once compiled, the data, in the form of condition codes, reflects the actual proportion of houses needing major, minor, and no renovation for each subsystem by house type. To accomplish this in the model, the data for each subsystem consists of an array of 10 discrete distributions stored as individual expressions in an EXPRESSIONS element.

Table 1. Input Data Requirements

	House Type:									
	CGO-3	CGO-4	FGO-3	FGO-4	SGO-4	SNCO-3	SNCO-4	JNCO-2	JNCO-3	JNCO-4
Subsystem/Renovation Level:										
Roof *(Structure, Covering, Pitch, Soffit/Fascia, Flashing, Gutters & Downspouts, Chimneys, Fire Walls)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Structural, Foundation/Exterior Walls *(Ext. Wall & Floor Structure & Covering; Foundation; Windows; Ext. Doors)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Mechanical *(Gas/Water Service, Water Heater, Heating/Cooling System, Ductwork, Registers/Diffusers, Fire Prot.)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Electrical *(Panel, Receptacles, Wiring, Smoke Detectors, Phone/Cable Jacks, Service Disconnect, Light Switches)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
General Interior (Excluding Kitchens & Baths) *(Flooring, Walls, Ceilings, Moldings, Stairs, Doors, Hardware)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Kitchen *(Cabinets, Countertops, Sink/Fixtures, Appliances, Vent Hood, Floors, Walls, Ceilings, Hardware)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Bath(s) *(Cabinets, Counters, Sink, Fixtures, Toilet, Tub/Shower, Floors, Walls, Ceilings, Ventilation, Hardware)*										
Minor	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T
Major	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T	C/$/T

C: Condition Data Required **$: Cost Data Required** **T: Completion Time Data Required**

The second data component is the project cost data for the various housing projects. This data was obtained through the use of the Air Force Parametric Cost Engineering System (PACES). PACES derives costs through a database of individual, or parametric, costs associated with individual construction tasks. Since the cost data derived from PACES is parametric in nature, it is very specific to the project that is being estimated. The simulation model, on the other hand, requires more general probability distributions of costs. To accomplish this, several estimates of various

renovation projects were obtained using PACES and this data was then used to select appropriate probability distributions. Specifically, minimum, most likely, and maximum estimates of project costs were obtained for each house type, subsystem, and degree of renovation (major and minor) resulting in 420 individual cost estimates. These estimates then served as parameters of individual triangular cost distributions for each house type, subsystem and degree of renovation. It was determined that this would be the most accurate approach for obtaining the cost data since PACES is the most widely used cost estimator for actual Air Force construction projects. The cost data distributions for each subsystem are stored in 2-dimensional arrays of size 10 by 3 to reflect 10 different house types and 3 possible levels of renovation (major, minor, or none). By storing the data in this way, the cost data can be accessed according to the house type and subsystem condition code.

The final data component is the estimated project completion times. Several sources including PACES, Page (1977), Thomas (1986), and Mossman (1995) were used to obtain estimates of the project completion times. Similar to the cost data, this type of data is also parametric in nature and therefore, several estimates must be made in order to obtain distributions suitable for use in a simulation model. Like the cost data, minimum, most likely, and maximum estimates of project completion times were obtained for each house type, subsystem, and degree of renovation. These estimates then served as parameters of individual triangular completion time distributions for each house type, subsystem and degree of renovation. The completion time data

distributions for each subsystem are also stored in 2-dimensional, 10 by 3 arrays and accessed according to house type and condition code.

Simulation Model Formulation

The next major step in the study involved the development of a suitable simulation model. The model can best be classified as a discrete event, non-terminating model. It is considered a discrete event or discrete change model because it deals with discrete entities (i.e. houses). Also, what happens to individual entities in the system is of primary interest. For this reason, a next event system of timekeeping is utilized (Shannon, 1975). The model is considered to be non-terminating because the system has neither a fixed starting condition nor a natural ending point (Pegden et al., 1995). Although for the purposes of this simulation, there is a fixed starting point at which we begin studying the system (i.e. a new fiscal year); there can be a variety of starting conditions depending on the previous year's activities. For example, if funding and time were sufficient to complete all projects in the previous year, then the system's starting condition will be empty and idle. However, since this is often not the case, various levels of queued but unexecuted projects are likely to exist at the beginning of the fiscal year. There is no natural ending point because there is a constant stream of projects entering the system.

The basic model used in this study is illustrated by the flow diagram in figure 1. The entities (which represent the houses in the actual system) enter the system through a CREATE block. Entities are created starting at time $t = 0$ and have triangularly distributed interarrival times. Next, each house is assigned a house type according to a

discrete distribution which represents the actual housing population at Barksdale AFB. Houses are also assigned their respective subsystem condition codes according to discrete distributions as described above. At this point, the house is checked using a BRANCH block to see if all subsystems meet standards. If so, the house is counted as a "good house" and the entity leaves the system. However, if one or more subsystem codes are below standards, the house continues through the system to be serviced.

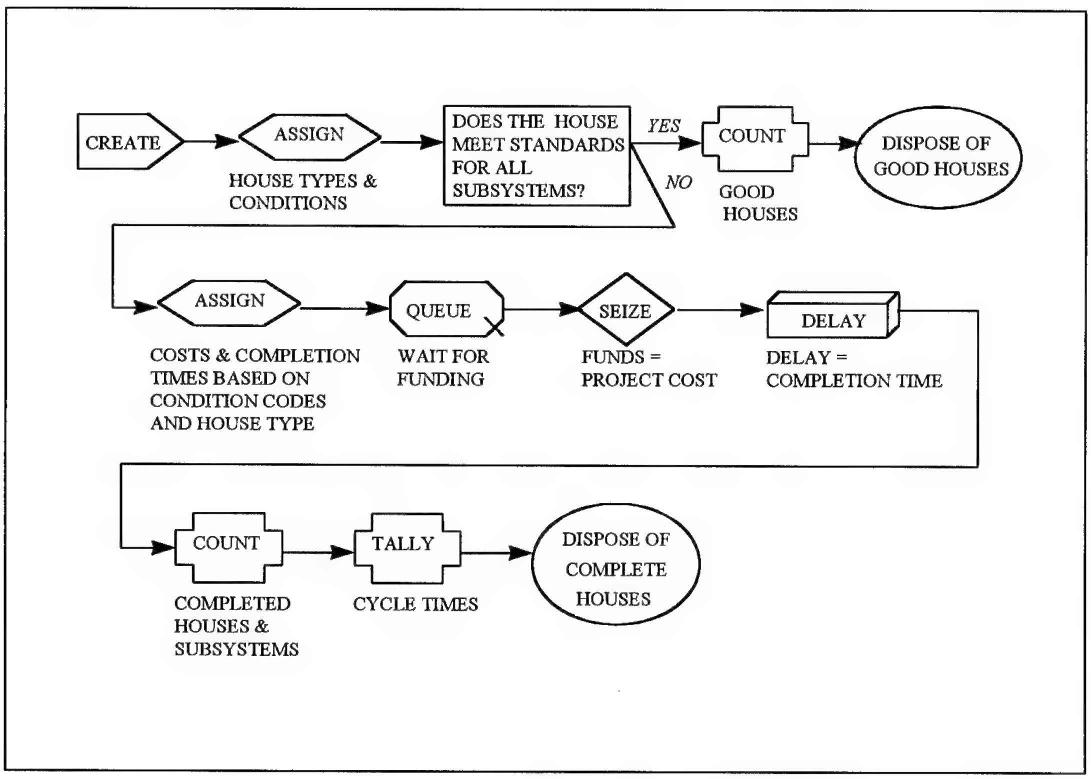


Figure 1. Basic Model Flow Diagram

Before the house can be serviced, it must first be assigned a cost and completion time based on the house type and subsystem condition codes. This is done through an iterative system of BRANCH blocks which checks each subsystem code and increments the cost if the code is below standards. The completion time assignments are handled similarly however, instead of being incremented, a maximum completion time is chosen. This is due to the assumption that work can be performed on all subsystems simultaneously, therefore the maximum completion time is chosen.

Once the house has been assigned a cost and completion time, it is ready to be serviced. In order to obtain service, the project must first receive funding. If funds are available, the entity immediately seizes an amount of funds equal to its respective project cost and is delayed for processing for a duration equal to its completion time. If, however, funds are not available, the project must wait in the project queue until more funding is allocated. For the purposes of this model, funds allocation can occur only at the beginning of the fiscal year.

The project queue is the primary focus of this study. In the standard model, the queue releases waiting houses according to a first-in, first-out (FIFO) discipline. Alternative models are identical to the standard model with the exception of the queueing discipline. Other queueing disciplines considered include: low value first according to total estimated project cost (LVF_Cost), high value first according to total estimated project cost (HVF_Cost), low value first according to estimated project completion time (LVF_CT), and high value first according to estimated project completion time (HVF_CT).

When work is completed on a house, it is counted as a complete house, its total time in the system is recorded and the house exits the system. Counts are also incremented with respect to the subsystem(s) which received service.

Pilot Runs, Verification, and Validation

Several pilot runs were performed on the standard model. The reasons for the pilot runs include: verification of the model, validation of the model, and determination of a warm-up period. A suitable sample size was also required prior to performance of the actual production runs.

Model Verification

Verification seeks to show that the computer program performs as expected and intended, thus providing a correct logical representation of the model (Pegden et al., 1995). Verification of the standard model was performed through the use of several test runs. These test runs were not only used to detect possible modeling errors, but also to test the model under a variety of conditions. Among these were varying the amounts of funding from low to high, varying the interarrival times, and changing the random number seeds to see how output and queue levels were affected.

Model Validation

Pegden et al. (1995) suggest that model validation is concerned with three basic questions:

1) Does the model adequately represent the real-world system?

2) Are the model-generated behavioral data characteristic of the real system's behavioral data?

3) Does the simulation model user have confidence in the model's results?

To attempt to answer these questions, the model was run under various conditions to test for reasonableness. Pilot runs also served to verify the structural and boundary characteristics of the model and to conduct sensitivity analyses to changes in the input conditions. Pegden et al. (1995) further state that because a model is constructed for a specific purpose, its validity can only be evaluated in terms of that purpose. Finally, one must keep in mind that a model's validity cannot be measured in absolute terms but is better viewed as existing on a continuum. It is the user's decision as to when a model has achieved the desired degree of validity for the intended purpose. Having performed the various pilot runs, it was decided that the model was indeed valid for the purposes of this study.

Determination of a Warm-up Period

As mentioned previously, a non-terminating system has no set initial conditions and no event that causes the system to return to a fixed initial condition. As a result, there is no natural basis for selecting the starting conditions or the run length. Since the system is non-terminating, its steady-state behavior over a long period of time is of primary interest. However, a non-terminating system generally is characterized by an initial transient or warm-up phase during which the distributions of the performance characteristics tend to change. This is known as non-stationarity of the performance characteristic distribution and is due to the fact that the simulation starts in an empty and idle state. This situation is not representative of the real system. In the real system,

we would expect to almost always have some entities in the system being serviced and waiting in queues.

Because it is desired to study the system's performance in steady-state, observations made during the transient phase will tend to bias results. In this study, the transient bias was dealt with simply by eliminating the observations made during the transient period. In order to determine the transient period, five replications of the model were run with each replication having a length of 1,825 days (five years). Cycle times, queue levels, and the total number of houses completed each year were recorded. For each replication, the number of houses completed in the first year was slightly greater and the cycle times were much lower than in subsequent years. This was to be expected since the houses entering the system in the first year had no houses ahead of them in the project queue. As stated previously, this is not a realistic starting condition and is not representative of the real system. During the remaining years of each replication, the queue levels were more steady and the total number of houses completed each year had leveled off.

The replication approach with a warm-up period of 365 days was selected for dealing with the transient phase in this study. Advantages to this approach are that it is simple to use and the fact that all statistical analysis can be performed directly on the outputs. The problem of auto-correlation is also eliminated with this approach. The disadvantage to this approach is that if the transient phase is substantial or if the computer run time per replication is long, discarding data at the beginning of each replication can result in much wasted computer time and data. Fortunately, computer

time required for a single replication was very small (about 10 seconds) and this was not a problem.

Determination of Sample Size

The final step before making production runs is determination of the number of replications (i.e. sample size) required to determine statistical significance of the performance characteristic. Shannon (1975) suggests two alternative methods for determining sample size: (1) Prior to and independent of the operation of the model, or (2) Based upon results generated by a pilot run.

The first method was chosen for this study. Where the central limit theorem can be applied and it can be assumed that no auto-correlation is present, a confidence interval approach can be applied to determine the sample size required for estimating the population mean. Suppose it is desired to determine an estimate $\overline{X}$ of the true population mean μ, such that

$$P\{\mu - d \leq \overline{X} \leq \mu + d\} = 1 - \alpha,$$

where $\overline{X}$ is the sample mean, μ is the true population mean, d is the allowable difference between the estimate and the true parameter, and $1 - \alpha$ is the probability that the interval $\mu \pm d$ contains $\overline{X}$. If a normality assumption is valid, it can be shown that

$$n = \frac{(Z_{\alpha/2}\sigma)^2}{d^2},$$

where n is the desired sample size, $Z_{\alpha/2}$ is the two-tailed standardized normal statistic with a probability of $1 - \alpha$, and σ is the sample variance.

Since the feasible range of outputs and the value of the true variance is not known, it was decided to make the estimate within the interval $\mu \pm \sigma/2$ with probability 0.95. Thus, $d = \sigma/2$ and $Z_{.025} = 1.96$ from the standard normal table. This gives a sample size of

$$n = \frac{(1.96\sigma)^2}{(\sigma/2)^2} = 16.$$

This is consistent with the suggestion of Pegden et al. (1995) who say that it is reasonable to make 10 to 20 replications and usually not beneficial to make more than 20 replications. For the purposes of this study, and since the computer time required per replication was so short, it was decided to set the number of replications at 20.

Production Runs

The fourth step of the study involved making various runs of the simulation model and collecting output data.

Determination of Run Length

Factors inherent to the real system were the key elements influencing the selection of the run length for each replication. The run length is essentially based upon the actual planning horizon that is available to programmers and decision makers in the MFH project planning and execution environment. As stated in the assumptions of this study, housing conditions and funding levels are assumed to remain constant over the next three years. It is with a high degree of certainty that this assumption can be made since these quantities are known for the next three years. However, beyond the three year point, there is very little that can be said with any degree of certainty about funding

levels or housing conditions. Funding levels for fiscal years (FYs) 1997 and 1998 are known and FY 1999 funding is being finalized as this study is being written. Beyond that point, however, there are simply too many variables that affect the funding process to make accurate predictions. Similarly, where housing conditions are concerned, it is possible to estimate normal wear and tear for only 3 to 4 years into the future. For these reasons, the run length for each replication was set at 1460 days (4 years). By truncating the transient period of each replication at 365 days, this gives a 3 year planning horizon which accurately reflects the real system. A one year planning horizon was also used to compare the short term performance of the various models.

Performance Characteristics

During the simulation runs, statistics were collected in several areas. These included the total number of houses completed over the course of the planning horizon (run length), total number of each type of project (subsystem) completed over the course of the planning horizon, average number of houses in queue, average cycle time over the course of the planning horizon, and average wait time (time in queue). The total number of houses completed over the course of the planning horizon and average number in queue were the performance characteristics of primary interest.

Output Analysis

The final step of this study involves the analysis of the output to determine various characteristics of the process. The main focus of this analysis will involve the comparison of the performance characteristics, namely the total number of houses completed and average number in queue, of the standard model with those of the

alternative models. Comparisons can be made by developing a confidence intervals on the expected value of d_i, where d_i is the difference between the performance characteristic of interest from the standard model and the alternative model on the *i*th replication. By doing this, the problem of comparing the two systems is reduced to estimating a single parameter. The resulting confidence interval is referred to as a paired-*t* confidence interval (Pegden et al., 1995).

The procedure for computing the confidence interval on the difference is similar to computing the confidence interval for a single system. First, the sample mean difference is calculated as

$$\bar{d} = \frac{\sum d_i}{n},$$

where $\bar{d}$ is the sample mean difference of the measured performance, d_i is the difference of the measured performance between the two models for replication i, and n is the sample size. The sample standard deviation, $s(d)$ is given by

$$s(d) = \sqrt{\frac{\sum (d_i - \bar{d})}{n-1}}.$$

Finally, the sample standard deviation of the mean difference is given by

$$s(\bar{d}) = \frac{s(d)}{\sqrt{n}}.$$

After the above quantities have been calculated, the half width for the 1 - α confidence interval on $\bar{d}$ is given by

$$h = t_{(n-1)(1-\alpha/2)} \times s(\bar{d}),$$

where $t_{(n-1)(1-\alpha/2)}$ is the tabulated student-t statistic at the (1 - $\alpha/2$) level of significance with (n - 1) degrees of freedom.

Recall that the $\bar{d}$ statistic is an estimate of the difference in the measured performance of the two models. Therefore, if the two systems perform identically, the expected value of $\bar{d}$ is 0. If the computed confidence interval contains 0, it cannot be stated with certainty that the two systems are different. On the other hand, if the interval does not contain 0, it can be stated at the appropriate confidence level that a difference does indeed exist between the two systems.

Since this study deals with comparing several alternative systems to a standard, the confidence levels for each of the comparisons must be made very carefully. Since several confidence interval statements will be made simultaneously, their individual levels must be adjusted upward so that the overall confidence level of all intervals' covering their respective targets is at the desired 1 - α level. The Bonferroni inequality states that if it is desired to make some number c of confidence interval statements, then each separate interval should be made at 1 - α/c, so that the overall confidence level associated with all intervals' covering their respective targets will be at least 1 - α (Law & Kelton, 1991).

In this study it was desired to have an overall confidence level of at least 0.95. Since we are making four comparisons to the standard, the Bonferroni inequality gives

$$C.L._r = 1 - \alpha/c,$$

$$C.L._r = 1 - 0.05/4 = 0.9875,$$

where $C.L._r$ is the required minimum confidence level at which individual comparisons must be conducted. Since the SIMAN Output Analyzer only allows comparison at the 0.90, 0.95, or 0.99 levels, 0.99 was chosen which gives an overall confidence level of 0.96 thus meeting the requirement of an overall 0.95 level.

CHAPTER IV

RESULTS AND CONCLUSIONS

DISCUSSION OF RESULTS

The results of this study are in the form of confidence intervals on means of the performance characteristics and paired-*t* comparisons as described in the previous chapter. Two primary performance characteristics were studied to determine what significant differences, if any, existed between the various models. These performance characteristics were (1) the total number of houses completed over the planning horizon (1 year or 3 years) and (2) the average number of houses in the queue over the planning horizon. A secondary performance characteristic is the average cycle time over the planning horizon.

Comparisons

The standard model and each of the four alternative models were run for 20 replications for each of two levels of the planning horizon (1 year and 3 years). A single sample for each performance characteristic was recorded at the end of each replication.

Total Number of Houses Completed

The total number of houses completed performance characteristic represents the maximum or final value of the *total complete* counter recorded at the end of each replication. A total of 10 runs (5 models with 2 planning horizon levels for each) of 20 replications each were made. For each run, a 0.95 confidence interval on the mean

number of houses completed was calculated. The results of the confidence interval calculations are given in table 2.

Table 2. 95% Confidence Intervals on the Mean for Total Number of Houses Completed

(1) Queueing Discipline	(2) Planning Horizon (yrs)	(3) Minimum	(4) Maximum	(5) Average	(6) Standard Deviation	(7) Half-Width
FIFO	1	68	82	73.9	3.81	1.78
LVF_Cost	1	70	84	75.4	3.78	1.77
HVF_Cost	1	68	82	73.9	3.81	1.78
LVF_CT	1	71	83	75.3	3.63	1.70
HVF_CT	1	69	84	74.4	3.93	1.84
FIFO	3	203	234	217	8.92	4.18
LVF_Cost	3	224	251	234	6.63	3.10
HVF_Cost	3	163	213	191	15.30	7.15
LVF_CT	3	214	244	225	7.50	3.51
HVF_CT	3	175	218	202	12.20	5.70

It is desired to complete the greatest number of houses as possible over the course of the planning horizon. For this reason, the higher the value of this performance characteristic, the better the performance. By examining the average values in column (5), slightly better performance seems to be indicated by the LVF_Cost and LVF_CT disciplines for both planning horizons. However, columns (6) and (7) show a fair degree of variability in the standard deviations and half-widths respectively among the various disciplines. For this reason, making inferences as to which discipline is best with respect to total number of houses completed would be premature at this point.

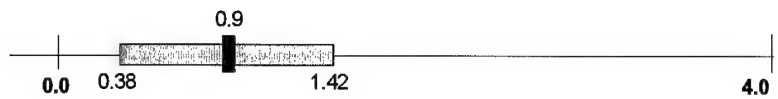
In order to make further conclusions, paired-*t* tests on the means between the various disciplines must be conducted. This was done in two ways. First, pairwise

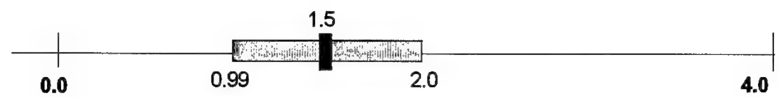
comparisons of various combinations of disciplines were made at the 0.95 confidence level. This procedure allowed several comparisons to be made, and also facilitated an iterative process by which the best of the alternatives could be selected. A summary of the various comparisons and their results are shown in tables 3, and 4.

In table 3, the first comparison shows that there is a clear and significant difference between the LVF_CT and HVF_CT disciplines with respect to the total number of houses completed. Similarly, the second comparison shows a significant difference between the LVF_Cost and HVF_Cost disciplines. In making these comparisons, the d_i's were obtained by subtracting the HVF values from the LVF values. Therefore, positive mean differences indicate that the LVF disciplines result in higher overall values for total number of houses completed. Since it is desired to find the best alternative, the two HVF disciplines can now be eliminated from further consideration.

Table 3. Pairwise Paired-*t* Comparisons of Total Number of Houses Completed, 1 Year Planning Horizon

Paired-*t* Comparison	Estimated Mean Diff.	Standard Deviation	Half-Width	Significant Difference?
(LVF_CT vs. HVF_CT)	0.9	1.12	0.524	Yes
(LVF_Cost vs. HVF_Cost	1.5	1.1	0.515	Yes
(LVF_Cost vs. LVF_CT)	0.1	0.553	0.259	No
(LVF_Cost vs. FIFO)	1.5	1.1	0.515	Yes
(LVF_CT vs. FIFO)	1.4	1.05	0.49	Yes





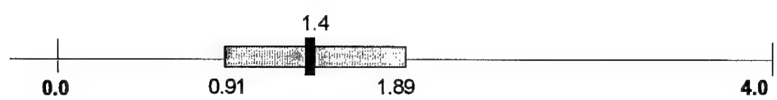
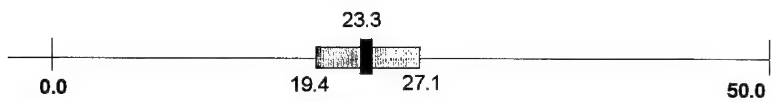
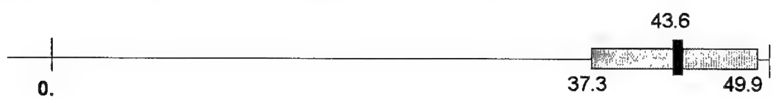


Table 4. Pairwise Paired-*t* Comparisons of Total Number of Houses Completed, 3 Year Planning Horizon

Paired-*t* Comparison	Estimated Mean Diff.	Standard Deviation	Half-Width	Significant Difference?
(LVF_CT vs. HVF_CT)	23.3	8.24	3.86	Yes
				
(LVF_Cost vs. HVF_Cos	43.6	13.5	6.31	Yes
				
(LVF_Cost vs. LVF_CT)	8.8	2.97	1.39	Yes
				
(LVF_Cost vs. FIFO)	17.4	6.24	2.92	Yes
				

The next step is to compare the LVF_Cost and LVF_CT comparisons. The results are shown in the third comparison of table 3 and indicate that there is no significant difference between the two disciplines. Because there is no significant difference, both of these disciplines must be compared with the standard (FIFO) discipline. As the last two comparisons in table 3 show, there are significant differences when the LVF_Cost and LVF_CT disciplines are compared with FIFO. Again, because these differences are positive, it can be stated that the two LVF disciplines perform

better than FIFO by an average of about 1.5 more houses completed over a 1 year planning horizon.

Comparisons of disciplines over a 3 year planning horizon are shown in table 4. Similar to the 1 year comparisons, the process is begun by comparing the LVF disciplines with their corresponding HVF disciplines. These results are shown in the first two comparisons of table 4. As may be expected, LVF_CT performs better than HVF_CT and LVF_Cost performs better than HVF_Cost for a 3 year planning horizon. Again, the two HVF disciplines are eliminated and the two LVF disciplines are compared as shown in the third comparison of table 4. Note that unlike the 1 year case, there is a significant difference between LVF_Cost and LVF_CT. Specifically, the LVF_Cost discipline allows the completion of an average of 8.8 more houses over a 3 year period. This significant difference facilitates the elimination of LVF_CT from further consideration. Finally, the LVF_Cost is now compared to the standard (FIFO) discipline. The last comparison of table 4 shows that LVF_Cost significantly outperforms FIFO.

The magnitudes of the mean differences should be noted. Notice that in the final comparison of table 4, LVF_Cost outperforms FIFO by over 17 houses completed over a 3 year period. In table 3, it is shown that the difference between these two disciplines was only about 1.5 houses over a 1 year period. Obviously, some increase in the mean difference should be expected simply due to the fact that the planning horizon is being lengthened. However, while the planning horizon is tripled, the mean difference increases over eleven times. Therefore, it can be stated that the improvements realized

by the LVF_Cost discipline over FIFO are not only increased; but are greatly magnified by the longer planning horizon.

The next comparisons made were of each of the alternative disciplines individually with FIFO at the 0.99 confidence level. By doing this, an overall comparison with FIFO at the 0.96 level can be achieved as explained in the previous chapter. Tables 5 and 6 provide the details of these comparisons.

Table 5. Five Alternative Queueing Disciplines

Discipline (*i*)	Description
1	First In, First Out (FIFO)
2	Low Value First according to Cost (LVF_Cost)
3	Low Value First according to Est. Completion Time (LVF_CT)
4	High Value First according to Cost (HVF_Cost)
5	High Value First according to Est. Completion Time (HVF_CT)

Table 6. Individual 99% Confidence Intervals for All Paired-*t* Comparisons of Mean Number Completed with the FIFO Discipline ($\mu_i - \mu_1$, i = 2,3,4,5); (* denotes a significant difference)

1 Year:				3 Years:			
i	X_i-X_1	Half-Width	Interval	i	X_i-X_1	Half-Width	Interval
2	1.5	0.704	(0.79, 2.2)*	2	17.4	3.99	(13.4, 21,4)*
3	1.4	0.669	(0.73, 2.07)*	3	8.6	2.55	(6.05, 11.2)*
4	0	0	N/A	4	-26.2	5.91	(-32.1, -20,3)*
5	0.5	0.487	(0.013, 0.98)*	5	-14.7	4.22	(-18.9, -10.4)*

Note that in these comparisons, the FIFO discipline is always subtracted from the alternative discipline to calculate the mean difference. Therefore, a positive mean

difference indicates that the alternative is better, and a negative mean difference indicates that FIFO is better.

Table 6 shows that for the 1 year planning horizon, all comparisons with FIFO except for HVF_Cost are significantly better than FIFO at the 0.99 level of significance. It is interesting to note that the HVF_Cost is essentially identical to FIFO resulting in a mean an half-width of 0. Also note that the results of these comparisons are consistent with the results of the pairwise comparisons for the 1 year planning horizon which showed the LVF_Cost discipline to be the best alternative.

Table 6 also shows that LVF_Cost and LVF_CT are significantly better than FIFO at the 3 year planning horizon. Again it is shown that LVF_Cost is the best alternative with a mean difference of over 17 houses when compared with FIFO. Note that at the 3 year planning horizon, the HVF_Cost and HVF_CT disciplines are both significantly worse than FIFO.

Average Number of Houses in Queue

The next performance characteristic to be studied was the average number of houses in the queue during the planning horizon. Similar to the total number of houses completed, 10 runs of 20 replications each were made. Again, for each run, a 0.95 confidence interval on the mean number in queue was calculated. The results are summarized in table 7.

Table 7. 95% Confidence Intervals on the Mean for the Average Number of Houses in the Queue

(1) Queueing Discipline	(2) Planning Horizon (yrs)	(3) Minimum	(4) Maximum	(5) Average	(6) Standard Deviation	(7) Half-Width
FIFO	1	13.5	32.7	22.7	5.99	2.80
LVF_Cost	1	12.1	32.7	21.5	6.03	2.82
HVF_Cost	1	13.5	32.7	22.7	5.99	2.80
LVF_CT	1	12.5	32.7	21.6	6.04	2.83
HVF_CT	1	13.5	32.7	22.2	5.96	2.79
FIFO	3	31.8	68.3	52.1	9.07	4.25
LVF_Cost	3	30.2	55.9	44.3	6.47	3.03
HVF_Cost	3	36.8	86.6	62.3	13.60	6.38
LVF_CT	3	30.8	62.7	47.7	7.87	3.68
HVF_CT	3	35.2	79.3	57.4	11.60	5.43

It is desired to keep the values of this performance characteristic as low as possible for a variety of reasons. First, high queue levels tend to decrease the number of houses which can be completed over the planning horizon and increase overall cycle times. Second, houses which are waiting to be worked on may or may not be able to be occupied by families depending on the nature of the work. Therefore, the more houses which are waiting for service, the fewer families which can be housed.

For the 1 year planning horizon, column 5 of table 7 shows only slight differences in the averages. For the 3 year case, greater differences are shown in column 5. As was the case with the total number completed performance characteristic, paired-*t* comparisons need to be conducted before inferences regarding significant differences can be made. As before, pairwise and individual comparisons with the FIFO discipline were conducted. Tables 8 and 9 show the results of the pairwise comparisons.

Table 8. Pairwise Paired-*t* Comparisons of Average Number of Houses in the Queue, 1 Year Planning Horizon

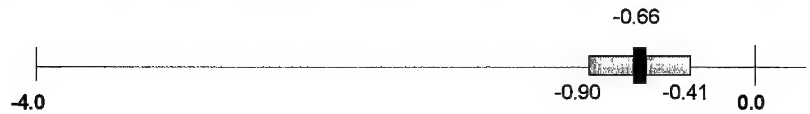
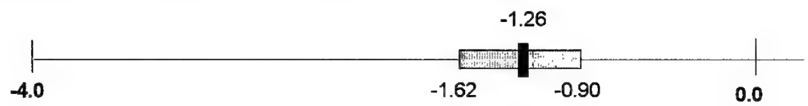
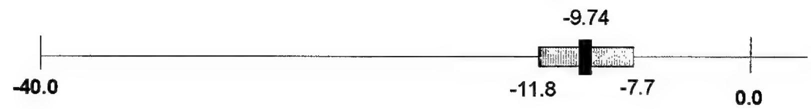
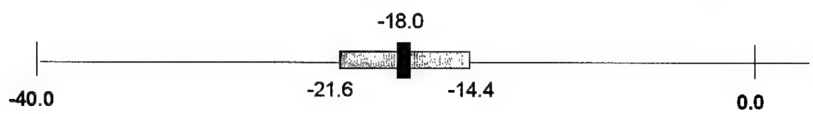
Paired-*t* Comparison	Estimated Mean Diff.	Standard Deviation	Half-Width	Significant Difference?
(LVF_CT vs. HVF_CT)	-0.66	0.53	0.248	Yes
				
(LVF_Cost vs. HVF_Cost	-1.26	0.77	0.358	Yes
				
(LVF_Cost vs. LVF_CT)	-0.11	0.32	0.148	No
				
(LVF_Cost vs. FIFO)	-1.26	0.77	0.358	Yes
				
(LVF_CT vs. FIFO)	-1.15	0.66	0.309	Yes
				

Table 9. Pairwise Paired-*t* Comparisons of Average Number of Houses in the Queue, 3 Year Planning Horizon

Paired-*t* Comparison	Estimated Mean Diff.	Standard Deviation	Half-Width	Significant Difference?
(LVF_CT vs. HVF_CT)	-9.74	4.38	2.05	Yes
(LVF_Cost vs. HVF_Cost	-18	7.64	3.58	Yes
(LVF_Cost vs. LVF_CT)	-3.37	1.58	0.738	Yes
(LVF_Cost vs. FIFO)	-7.76	2.87	1.34	Yes





Recall that it is desired to choose the alternative which has the minimum average number of houses in the queue. Therefore, if the same comparisons are made for average number in queue as were made for the total number of houses completed, mean differences which are negative are desired. Table 8 shows the LVF disciplines as having better performance than the respective HVF disciplines. Also, the comparison of the two LVF alternatives shows no significant difference with respect to average number in queue. As a result, both LVF disciplines are compared to FIFO resulting in significantly better performance from both.

When comparisons are made for the 3 year planning horizon in table 9, similar results are obtained. The LVF disciplines show significant differences when compared to the HVF disciplines. However, a slight difference is noticed between the LVF_Cost and LVF_CT disciplines for the 3 year planning horizon. Specifically, LVF_Cost is better than LVF_CT by a mean difference of -3.37 houses in queue. Finally, LVF_Cost is compared to FIFO and shows superior performance with a mean difference of -7.76 houses in queue.

Individual comparisons with FIFO at the 0.99 level of significance were performed next. The results of these comparisons are shown in table 10.

Table 10. Individual 99% Confidence Intervals for All Paired-*t* Comparisons of Mean Number in Queue with the FIFO Discipline ($\mu_i - \mu_1$, i = 2,3,4,5); (* denotes a significant difference)

1 Year:				3 Years:			
i	X_i-X_1	Half-Width	Interval	i	X_i-X_1	Half-Width	Interval
2	-1.26	0.490	(-1.75, -0.77)*	2	-7.76	1.84	(-9.6, -5.92)*
3	-1.15	0.423	(-1.57, -0.73)*	3	-4.39	1.05	(-5.44, -3.34)*
4	0	0	N/A	4	10.3	3.32	(6.94, 13.6)*
5	-0.5	0.362	(-0.86, -0.13)*	5	5.35	2.20	(3.15, 7.55)*

Again, recall that in these comparisons, the FIFO discipline is subtracted from the alternative discipline to calculate mean differences. Therefore, since it is desired to find the alternative with the minimum average number in queue, a negative difference indicates that the alternative is better, and a positive difference shows that FIFO is better.

Table 10 shows that for the 1 year planning horizon, comparisons 2, 3, and 5 are better than FIFO at the 0.99 level of significance. Also, note that the LVF_Cost alternative (comparison 2) seems to be the best showing a mean difference of -1.26 houses in queue. For the 3 year planning horizon, the HVF alternatives are significantly worse than FIFO, and the LVF alternatives are significantly better than FIFO. Specifically, the LVF_Cost discipline gives a mean difference of -7.76 houses in queue when compared with FIFO over a 3 year planning horizon. These results are consistent with those obtained from the pairwise comparisons.

Average Cycle Time

Average cycle time was studied as a secondary performance characteristic. Similar to the two primary performance characteristics, 10 runs of 20 replications each were made. Again, for each run, a 0.95 confidence interval on the average cycle time was calculated. These results are summarized in table 11.

Table 11. 95% Confidence Intervals on the Mean for Average Cycle Time (in Days)

(1) Queueing Discipline	(2) Planning Horizon (yrs)	(3) Minimum	(4) Maximum	(5) Average	(6) Standard Deviation	(7) Half-Width
FIFO	1	30.5	66.4	46.3	8.38	3.92
LVF_Cost	1	28.1	66.4	44.0	8.69	4.07
HVF_Cost	1	30.5	66.4	46.3	8.38	3.92
LVF_CT	1	28.7	66.4	44.3	8.65	4.05
HVF_CT	1	30.5	66.4	45.5	8.34	3.90
FIFO	3	84.3	188	139	28.6	13.40
LVF_Cost	3	78.0	143	116	18.4	8.60
HVF_Cost	3	76.6	129	111	16.5	7.72
LVF_CT	3	77.3	144	115	18.4	8.63
HVF_CT	3	79.8	132	113	17.0	7.96

For this performance characteristic it is desired to find the alternative which has the lowest average cycle time. Again only slight differences in the averages are noticed when the confidence interval data is examined directly. Therefore, paired-*t* comparisons must be conducted once again. Since this is a secondary performance characteristic, it is only desired to compare the various alternative disciplines to the standard (FIFO) discipline. For this reason, pairwise comparisons were not conducted for this performance characteristic. Results of the individual paired-*t* tests at the 0.99 level of significance are provided in table 12.

Table 12. Individual 99% Confidence Intervals for All Paired-*t* Comparisons of Average Cycle Time (in Days) with the FIFO Discipline ($\mu_i - \mu_1$, i = 2,3,4,5); (* denotes a significant difference)

1 Year:				3 Years:			
i	X_i-X_1	Half-Width	Interval	i	X_i-X_1	Half-Width	Interval
2	-2.24	1.11	(-3.35, -1.13)*	2	-23.1	7.50	(-30.6, -15.6)*
3	-2	0.83	(-2.83, -1.18)*	3	-24.2	7.97	(-32.2, -16.2)*
4	0	0	N/A	4	-28.6	9.64	(-38.2, -19)*
5	-0.78	0.62	(-1.4, -0.156)*	5	-26.9	8.88	(-35.8, -18.1)*

Since lower cycle times are preferred, and the average cycle times for the FIFO discipline are subtracted from the alternative to which it is being compared, negative average differences indicate better performance. As table 12 shows, all comparisons made with the exception of HVF_Cost vs. FIFO (comparison 4) show better performance than FIFO. For the 1 year planning horizon, the LVF_Cost seems to be the best alternative. However, unlike the previous performance characteristics, this is

not the case for the 3 year planning horizon. Although all appear to be far better than FIFO, here it seems that HVF_Cost seems to be slightly better than the others if only mean difference is considered. It should be noted that this comparison also has the widest confidence interval with a half width of 9.64.

CONCLUSIONS

The above results indicate that when projects waiting in queue are ranked according to low value first with respect to cost, overall performance is improved. In fact, the LVF_Cost discipline proved to be superior for both of the primary performance measures, total number of houses completed and average number in queue. Although it was not the best for the secondary performance measure, average cycle time, it still showed significant improvements over the standard (FIFO) discipline and had the narrowest paired-*t* confidence interval when compared to FIFO.

Queueing projects according to low value first with respect to estimated completion time also showed significant improvement over the FIFO discipline for all performance measures. However, this would probably not be the best method for ranking projects since accurately estimating completion times can prove to be a much more difficult task. External factors such as weather, labor and/or material shortages, and other work stoppages tend to have more severe effects on the completion time of a project than on the overall cost.

LIMITATIONS

A major limitation in this study is the reliance on the assumption that the cost and subsystem condition code distributions will essentially remain constant over time. Although these are not unreasonable assumptions for the relatively short planning horizons that were considered here, they do make the model rather inflexible should longer planning horizons need to be studied.

Similarly, the assumption that the budget will essentially remain constant over the planning horizon, may not be realistic in all cases. However, since budgets are normally known for at least a few years into the future, the model can be easily modified to accommodate fluctuating budgets.

Finally, more in-depth analysis of project completion time input data may yield slightly better model performance. The use of actual historical data fit to appropriate distributions may facilitate better analysis than the use of triangular distributions in this area.

RECOMMENDATIONS FOR FUTURE RESEARCH

The incorporation of life-cycle data into the RPM model is currently underway. This data will enable to analyst to foresee or predict future subsystem conditions from existing RPM data alone. The incorporation of life-cycle data, when available, into a simulation model would be of great benefit. This would facilitate the testing of various scenarios which the installation Civil Engineer could use to make future MFH renovation and maintenance decisions.

Another recommendation would be the development of a computer interface that would link the RPM database and the PACES cost estimation software with a discrete event simulation software package. This would allow fast and easy development of future models.

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